AN ARTIFICIAL NEURAL NETWORK APPROACH FOR CLASSIFICATION AND PREDICTION OF LOW PRESSURE CHEMICAL VAPOR DEPOSITION Si_XN_Y ISFET PH SENSOR DRIFT

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Sensor bagi transistor bersifat ion memilih kesan-lapangan (ISFET) adalah sensor lapangan dimana ion di dalam sesuatu sampel media mengalami pelbagai persekitaran yang mempengaruhi tindakbalas molekul sediada dan bertumpu di lapisan gerbang oksida. Satu perubahan dari segi caj elektrik berlaku dan memberi kesan terhadap konduktans dalam saluran ISFET. Akibatnya, perubahan konduktans dalam sumber dan saluran menghasilkan isyarat elektrik. Masalah yang biasa berlaku ialah berlakunya hanyutan voltan semasa isyarat elektrik beransur berubah dengan bebas daripada sampel yang diukur. Objektif utama kajian adalah untuk membina satu model berdasarkan jaringan neutral buatan yang boleh digunapakai untuk mengklasifikasi dan meramal kesilapan serta melaksanakan pampasan drift dalam sensor pemendapan wap kimia Si_xN_y ISFET pH. Model yang sedemikian boleh digunakan untuk menghadapi masalah hanyutan voltan yang biasanya wujud dalam sensor kimia. Tiga unit sensor ISFET telah digunakan untuk menentukur tiga jenis larutan penampan pH iaitu pH 4, pH 7 dan pH 10. Rangkaian neural buatan telah digunakan untuk membina satu model kotak hitam berbilang input dan output data ISFET. Satu nilai peratusan ketepatan telah digunakan untuk menaksir prestasi model dari segi pengkelasan, sementara min ralat kuadrat (MSE) dan parameter koefisien penentuan (R^2) digunakan bagi menentukan model terbaik dalam meramalkan kesilapan sensor ISFET. Dari segi struktur model dalam aspek klasifikasi, Pengenalan Corak Rangkaian Neural (PATTERNET) terbukti berfungsi lebih efisien daripada Rangkaian Fungsi Fitting (FITNET) dengan ketepatan 100%. Konfigurasi rangkaian PATTERNET dengan dwi-lapisan 30 nod pada lapisan tersembunyi pertama dan 3 nod pada lapisan tersembunyi kedua, mencapai keputusan terbaik. Dari segi ramalan, model NARX-BR, dengan 75 kelewatan, merupakan model yang cekap dalam meramalkan kesilapan set data ISFET. Nilai MSE = $4.881e^{-5}$ dan R^2 = 0.99930 bagi model NARX-BR menunjukkan model mampu meramalkan ralat. Pampasan drift telah dilaksanakan dan isu kehanyutan dalam sensor ISFET telah berjaya diatasi. Kajian ini menunjukkan potensi yang ketara dalam pembangunan rangkaian neural buatan untuk menghalang isu hanyutan voltan dalam sensor tekanan rendah wap kimia Si_xN_y ISFET pH.

ABSTRACT

A sensor in an ion selective field-effect transistor (ISFET) is a field sensor in which ions within a sample media undergo multiple environments affecting reactions occurring molecules to concentrate at the gate oxide layer. A change in electrical charge occurs and it affects the conductance in the ISFET channels. Consequently, the change in conductance within the source and the drain produce an electrical signal. The most common problem is the occurrence of drift when the electrical signal output gradually changes independent of the measured sample. The primary objective of the present study is to investigate a reliable model based on artificial neural network to classify and forecast errors as well as to implement the drift compensation in low-pressure chemical vapour deposition Si_xN_y ISFET pH sensor. Such model could be used to encounter voltage drift problems that usually exist in chemical sensors. Three units of ISFET sensors were used to calibrate with three types of pH buffer solutions that are pH 4, pH 7 and pH 10. Artificial neural networks were applied to construct a black-box with multiple inputs and outputs models of the ISFET data. A percentage accuracy value was used to assess the model's performances in terms of classification, while the mean squared error (MSE) and the coefficient of determination (R^2) parameter were used to determine the best models in predicting errors in the ISFET sensors. On the model's structure in classification, Pattern Recognition Neural Network (PATTERNNET) proved to perform better than Function Fitting (FITNET) networks with 100% accuracy. The network configuration in PATTERNNET, a dual-layered network with 30 nodes on the first hidden layer and 3 nodes on the second hidden layer achieved the best results. As for prediction, the NARX-BR model with 75 delays produced an efficient model in predicting errors in ISFET data set. The value of MSE = $4.8814e^{-5}$ and R^2 = 0.99930 for the NARX-BR model showed that the model is capable of predicting errors. The drift compensation was applied and the drift issues in the ISFET sensors were successfully resolved. The present study demonstrates significant potentials in the development of artificial neural networks to stave off voltage drift issues in ISFET low-pressure chemical vapour deposition Si_xN_y ISFET pH sensor.

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LIST OF ABBREVIATIONS

AANN	Auto-Associative Neural Network
ANN	Artificial Neural Network
APS	Active Pixel Sensor
BPN	Backpropagation Neural Network
BR	Bayesian Regularization
CBPN	Cascade Forward Back Propagation Neural Network
CMOS	Complementary Metal-Oxide-Semiconductor
CSV	Comma-Separated Values
CTAT	Complementary To Absolute Temperature
DNA	Deoxyribonucleic Acid
DTDNN	Distributed Time-Delay Neural Network
FITNET	Function Fitting Neural Network
IGFET	Insulated-Gate Field-Effect Transistor
ISE	Ion-Selective Electrode
ISFET	Ion-Sensitive Field-Effect Transistor
LM	Levenberg-Marquardt
LPCVD	Low Pressure Chemical Vapor Deposition
MLP	Multilayer Perceptron
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MSE	Mean Squared Error
MSPCA	Multiscale Principle Component Analysis
NAR	Nonlinear Autoregressive
NARX	Nonlinear Autoregressive With External Input
NMOS	Negative Channel Metal-Oxide-Semiconductor
PATTERNNET	Pattern Recognition Neural Network
PWM	Pulse With Modulation
REFET	Reference Field-Effect Transistor
SOM	Self-Organizing Map
TDNN	Time Delay Neural Network

REFERENCES

Abdullah, W. F. H., Othman, M., & Ali, M. A. M. (2008). Ion-selective field-effect transistor sensor response for neural network supervised learning. *IEEE International Conference on Semiconductor Electronics, Proceedings, ICSE*, 126–129. https://doi.org/10.1109/SMELEC.2008.4770291

Abdullah, W. F. H., Othman, M., Ali, M. A. M., & Islam, M. S. (2010). Improving ion-sensitive field-effect transistor selectivity with backpropagation neural network. *WSEAS Transactions on Circuits and Systems*, *9*(11), 700–712.

Abdullah, W. F. H., Othman, M., Ali, M. A. M., & Islam, M. S. (2010). Knowledge representation of ion-sensitive field-effect transistor voltage response for potassium ion concentration detection in mixed potassium/ammonium ion solutions. *American Journal of Applied Sciences*, *7*(1), 81–88. https://doi.org/10.3844/ajassp.2010.81.88

Asad, S., & Division, M. E. (2012). Observing of pH for Titration Process with Hybrid, *10*(2), 264–271.

Akangah, P., Parrish, L., Ofori-Boadu, A., & Davis, F. (2018). *2018 ASEE Southeastern Section Conference Predicting Academic Achievement in Fundamentals of Thermodynamics using Supervised Machine Learning Techniques*.

Al-allaf, O. N. A., Tamimi, A. A., & Abdalkader, S. a. (2012). Artificial Neural Networks for Iris Recognition System : Comparisons between Different Models , Architectures and Algorithms, *2*(10), 744–752.

Al-sbou, Y. A., & Alawasa, K. M. (2017). Nonlinear Autoregressive Recurrent Neural Network Model For Solar Radiation Prediction. *International Journal of Applied Engineering Research*, *12*(14), 4518–4527.

Azad, A. K., Wang, L., Guo, N., Tam, H., & Lu, C. (2016). Signal processing using artificial neural network for BOTDA sensor system, *24*(6), 6769–6782. https://doi.org/10.1364/OE.24.006769

Aziz, N. A., Al, M., Abdul, K., Fazlida, W., Abdullah, H., Tahir, N., & Alam, S. (2013). Hardware Implementation of Backpropagation Algorithm based on CHEMFET Sensor Selectivity, 387–390.

Barabash, P. R., Cobbold, R. S. C., & Wlodarski, W. B. (1987). Analysis of the Threshold Voltage and Its Temperature Dependence in Electrolyte-Insulator-, (6), 1271–1282.

Bakshi, B. R. (1998). Multiscale PCA with application to multivariate statistical process monitoring. *AIChE Journal*, *44*(7), 1596–1610. https://doi.org/10.1002/aic.690440712

Bergveld, P. (1972). Development, Operation, and Application of the Ion-Sensitive

Field-Effect Transistor as a Tool for Electrophysiology. *IEEE Transactions on Biomedical Engineering*, *BME-19*(5), 342–351. https://doi.org/10.1109/TBME.1972.324137

Bergveld, P. (2003). Thirty years of ISFETOLOGY. *Sensors and Actuators B: Chemical*, *88*(1), 1–20. https://doi.org/10.1016/S0925-4005(02)00301-5

Bhardwaj, R., Majumder, S., & Pawan, K. (2017). Temperature Compensation of ISFET Based pH Sensor Using Artificial Neural Networks, 155–158.

Binti, N., & Aziz, A. (2015). Comparison Between MLP And RBF Network In Improving CHEMFET Sensor Selectivity, (1), 165–170.

Bratov, A., Abramova, N., & Domínguez, C. (2004). Investigation of chloride sensitive ISFETs with different membrane compositions suitable for medical applications. *Analytica Chimica Acta*, *514*(1), 99–106. https://doi.org/10.1016/j.aca.2004.01.034

Bukhari, F., Suah, M., Ahmad, M., & Nasir, M. (2003). Optimisation of the range of an optical fibre pH sensor using feed-forward artificial neural network, *90*, 175–181. https://doi.org/10.1016/S0925-4005(03)00025-X

Burtseva, L., Gonzalez-Navarro, F. F., Stoytcheva, M., Estrella Sato, A. S., & Garcia Curiel, E. R. (2014). Modelling the influence of pH and Temperature on the response of an acetylcholinesterase biosensor using Machine Learning Methods. *Biosensors: Recent Advances and Mathematical Challenges*, 185–202. https://doi.org/10.3926/oms.189

Capel-cuevas, S. (2012). A Compact Optical Instrument with Artificial Neural Network for pH Determination, 6746–6763. https://doi.org/10.3390/s120506746

Chang, K. M., Chang, C. T., Chao, K. Y., & Lin, C. H. (2010). A novel pH-dependent drift improvement method for zirconium dioxide gated pH-ion sensitive field effect transistors. *Sensors*, *10*(5), 4643–4654. https://doi.org/10.3390/s100504643

Chen, D. Y., & Chan, P. K. (2008). An intelligent ISFET sensory system with temperature and drift compensation for long-term monitoring. *IEEE Sensors Journal*, *8*(12), 1948–1959. https://doi.org/10.1109/JSEN.2008.2006471

Chin, Y. L., Chou, J. C., Sun, T. P., Chung, W. Y., & Hsiung, S. K. (2001). A novel pH sensitive ISFET with on chip temperature sensing using CMOS standard process. *Sensors and Actuators, B: Chemical*, *76*(1–3), 582–593. https://doi.org/10.1016/S0925-4005(01)00639-6

Cho, W., & Lim, C. (2017). Sensing properties of separative paper-based extended-gate ion-sensitive field-effect transistor for cost effective pH sensor applications. *Solid State Electronics*. https://doi.org/10.1016/j.sse.2017.10.025

Chung, W.-Y., G. Cruz, F. R., Yang, C.-H., He, F.-S., Liu, T.-T., G., D., … Jarosewicz, B. (2010). CMOS Readout Circuit Developments for Ion Sensitive Field Effect Transistor Based Sensor Applications. *Solid State Circuits Technologies*, (January). https://doi.org/10.5772/6891

Ciosek, P., & Wróblewski, W. (2006). The analysis of sensor array data with various pattern recognition techniques. *Sensors and Actuators, B: Chemical*, *114*(1), 85–93. https://doi.org/10.1016/j.snb.2005.04.008

Constandinou, T. G., Prodromakis, T., Liu, Y., Toumazou, C., & Georgiou, P. (2011). An Extended CMOS ISFET Model Incorporating the Physical Design Geometry and the Effects on Performance and Offset Variation. *IEEE Transactions on Electron Devices*, *58*(12), 4414–4422. https://doi.org/10.1109/ted.2011.2168821

Cuéllar, M. P., Capitán-Vallvey, L. F., Capel-Cuevas, S., de Orbe-Payá, I., & Pegalajar, M. C. (2010). Full-range optical pH sensor array based on neural networks. *Microchemical Journal*, *97*(2), 225–233. https://doi.org/10.1016/j.microc.2010.09.008

Daniel, M., Janicki, M., & Napieralski, A. (2003). Simulation of ion sensitive transistors using a SPICE compatible model. *Proceedings of IEEE Sensors 2003 (IEEE Cat. No.03CH37498)*, *1*, 543–548. https://doi.org/10.1109/ICSENS.2003.1278997

Das, M. P., & Bhuyan, M. (2014). New ISFET interface circuits with noise reduction capability. *International Conference on Recent Advances and Innovations in Engineering, ICRAIE 2014*. https://doi.org/10.1109/ICRAIE.2014.6909263

Del Valle, M. (2012). Sensor Arrays and Electronic Tongue Systems. *International Journal of Electrochemistry*, *2012*, 1–11. https://doi.org/10.1155/2012/986025

Del-Rey-Maestre, N., Mata-Moya, D., Jarabo-Amores, M. P., Gomez-del-Hoyo, P. J., & Barcena-Humanes, J. L. (2018). Artificial intelligence techniques for small boats detection in radar clutter. Real data validation. *Engineering Applications of Artificial Intelligence*, *67*(July 2017), 296–308. https://doi.org/10.1016/j.engappai.2017.10.005

Devi, S. R., Arulmozhivarman, P., Venkatesh, C., & Agarwal, P. (2016). Performance comparison of artificial neural network models for daily rainfall prediction. *International Journal of Automation and Computing*, *13*(5), 417–427. https://doi.org/10.1007/s11633-016-0986-2

Dinar, A. M., Zain, A. S. M., & Salehuddin, F. (2017). CMOS ISFET device for DNA Sequencing: Device compensation, application requirements and recommendations. *International Journal of Applied Engineering Research*, *12*(21), 11015–11028.

Dinar, A. M., Suhaila, A., Zain, M., & Salehuddin, F. (2018). Utilizing of CMOS ISFET sensors in DNA applications detection : A systematic review Utilizing of CMOS ISFET sensors in DNA Applications Detection : A Ssystematic Review, (May).

Duckworth, P., Hogg, D. C., & Cohn, A. G. (2019). Unsupervised human activity analysis for intelligent mobile robots. *Artificial Intelligence*, *270*, 67–92. https://doi.org/10.1016/j.artint.2018.12.005

Elyasi, A., Fouladian, M., & Jamasb, S. (2018). Counteracting Threshold-Voltage Drift in Ion-Selective Field Effect Transistors (ISFETs) Using Threshold-Setting Ion Implantation. *IEEE Journal of the Electron Devices Society*, *6*, 747–754. https://doi.org/10.1109/JEDS.2018.2847740

Fan, N., Wang, S., Liu, C., & Liu, X. (2018). Wheel Wear Prediction of High-Speed Train Using NAR and BP Neural Networks. *Proceedings - 2017 IEEE International Conference on Internet of Things, IEEE Green Computing and Communications, IEEE Cyber, Physical and Social Computing, IEEE Smart Data, IThings-GreenCom-CPSCom-SmartData 2017*, *2018–Janua*, 126–130. https://doi.org/10.1109/iThings-GreenCom-CPSCom-SmartData.2017.24

Garcia-Breijo, E., Atkinson, J., Gil-Sanchez, L., Masot, R., Ibañez, J., Garrigues, J., … Olguin, C. (2011). A comparison study of pattern recognition algorithms implemented on a microcontroller for use in an electronic tongue for monitoring drinking waters. *Sensors and Actuators, A: Physical*, *172*(2), 570–582. https://doi.org/10.1016/j.sna.2011.09.039

Gao, J., & Jamidar, R. (2014). Machine Learning Applications for Data Center Optimization. *Google White Paper*, 1–13.

Georg, J. (2014). Assessing neural networks for sensor fault detection. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6841441

Georgiou, P., & Toumazou, C. (2009). ISFET characteristics in CMOS and their application to weak inversion operation. *Sensors and Actuators, B: Chemical*, *143*(1), 211–217. https://doi.org/10.1016/j.snb.2009.09.018

Gonz, A., Cet, X., & Valle, M. (2018). A Voltammetric Electronic Tongue for the Resolution of Ternary Nitrophenol Mixtures, 1–11. https://doi.org/10.3390/s18010216

Gumbrecht, W., Schelter, W., Montag, B., Rasinski, M., & Pfeiffer, U. (1990). Online blood electrolyte monitoring with a ChemFET microcell system. *Sensors and Actuators: B. Chemical*, *1*(1–6), 477–480. https://doi.org/10.1016/0925-4005(90)80253-V

Guzman, S. M., Paz, J. O., & Tagert, M. L. M. (2017). The Use of NARX Neural Networks to Forecast Daily Groundwater Levels. *Water Resources Management*, *31*(5), 1591–1603. https://doi.org/10.1007/s11269-017-1598-5

Hanim Abdullah, W. F., Othman, M., Mohd Ali, M. A., & Islam, M. S. (2011). Ion-sensitive field-effect transistor selectivity with back-propagation neural network. *International Conference on Electronic Devices, Systems, and Applications*, 314–317. https://doi.org/10.1109/ICEDSA.2011.5959093

Hu, Y., & Georgiou, P. (2014). A Robust ISFET pH-Measuring Front-End for. *IEEE Transactions on Biomedical Circuits and Systems*, *8*(2), 177–185.

Ir, P., Em, P. B., & Ee, F. (2003). ISFET , Theory and Practice, (October), 1–26.

Jamasb, S. (2004). An analytical technique for counteracting drift in ion-selective field effect transistors (ISFETs). *IEEE Sensors Journal*, *4*(6), 795–801. https://doi.org/10.1109/JSEN.2004.833148

Jamasb, S. (2016). A Time-domain Method for Correction of Instability in Sensors Based on Field Effect Transistors (FETs). *International Journal Circuits, Systems and Signal Processing*, *10*.

Jamasb, S., Collins, S., & Smith, R. L. (1998). A physical model for drift in pH ISFETs. *Sensors and Actuators, B: Chemical*, *49*(1–2), 146–155. https://doi.org/10.1016/S0925-4005(98)00040-9

Jeatrakul, P., & Wong, K. W. (2009). Comparing the performance of different neural networks for binary classification problems. *2009 8th International Symposium on Natural Language Processing, SNLP '09*, 111–115. https://doi.org/10.1109/SNLP.2009.5340935

Jha, G. K. (2007). *Artificial Neural Networks and its Applications*.

Jiao, L., & Barakat, N. (2012). Ion-Sensitive Field Eect Transistor as a PH Sensor Ion-Sensitive Field Effect Transistor as a PH Sensor. *Journal of Nanoscience and Nanotechnology*, *12*, 1–5. https://doi.org/10.1166/jnn.2012.6065

Kadir, R. A., Rofei, M., Hussin, M., & Syono, M. I. (2011). TCAD Process Simulation for Light Effect Improvement of Ion Sensitive Field Effect Transistor, 19–23.

Kalofonou, M., & Toumazou, C. (2014). A Low Power Sub-μW chemical gilbert cell for isfet differential reaction monitoring. *IEEE Transactions on Biomedical Circuits and Systems*, *8*(4), 565–574. https://doi.org/10.1109/TBCAS.2013.2282894

Kang, J., & Cho, W. (2019). Improved pH Sensitivity and Reliability for Extended Gate Field-Effect Transistor Sensors Using High- k Sensing Membranes, *19*(3), 1425–1431. https://doi.org/10.1166/jnn.2019.16222

Kaur, H., Singh, G., & Minhas, J. (2013). A Review of Machine Learning based Anomaly Detection Techniques. *International Journal of Computer Applications Technology and Research*, *2*(2), 185–187. https://doi.org/10.7753/ijcatr0202.1020

Kayri, M. (2016). Predictive Abilities of Bayesian Regularization and Levenberg–Marquardt Algorithms in Artificial Neural Networks: A Comparative Empirical Study on Social Data. *Mathematical and Computational Applications, 21*(2), 20. https://doi.org/10.3390/mca21020020

Koch, S., Curtis, G., Hughes, H., Cefai, J., Barrow, D., Müller, E., & Woias, P. (2002). An ISFET-FIA system for high precision pH recording. *Sensors and Actuators B: Chemical*, *15*(1–3), 68–74. https://doi.org/10.1016/0925-4005(93)85029-a

Koval, S. I. (2018). *Data Preparation in Neural Network Data Analysis*. 39–62. https://doi.org/10.1007/978-0-387-71720-3_3

Kumar, K., & Thakur, G. S. M. (2012). Advanced Applications of Neural Networks and Artificial Intelligence: A Review. *International Journal of Information Technology and Computer Science*, *4*(6), 57–68. https://doi.org/10.5815/ijitcs.2012.06.08

Lee, S. K., & Choi, S. Y. (2010). Improvement of drift characteristic to continuously measure Al 2 O 3 pH-ISFET with the protective structure. *The Electrochemical Society*, 38–46.

Lee, C. S., Kyu Kim, S., & Kim, M. (2009). Ion-sensitive field-effect transistor for biological sensing. *Sensors*, *9*(9), 7111–7131. https://doi.org/10.3390/s90907111

Lean Yu, Shouyang Wang, K. K. L. (2006). An integrated data preparation scheme for neural network data analysis. *Ieee Transactions on Knowledge and Data Engineering*, *18*(2), 217–230. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.93.7826

Lu, C., Hou, T., & Pan, T. (2018). High-Performance Double-Gate α-InGaZnO ISFET pH Sensor Using a HfO2 Gate Dielectric, *65*(1), 237–242.

Lou, M. (1993). *Preprocessing data for neural networks,* Technical Analysis of Stocks & Commodities Magazine

M. V. Kukade, N. M. Kulkarni, D. S. Kumbhar, D. C. G. (2018). Identification of spices by Electronic Nose using pattern recognition technique. *International Journal on Future Revolution in Computer Science & Communication Engineering*, *4*(3), 243 – 250.

Mahmoudabadi, A. (2010). Comparison of weighted and simple linear regression and artificial neural network models in freeway accidents prediction (Case study: Qom & Qazvin Freeways in Iran). *2nd International Conference on Computer and Network Technology, ICCNT 2010*, (May 2010), 392–396. https://doi.org/10.1109/ICCNT.2010.73

Martinoia, S., & Massobrio, G. (2000). Behavioral macromodel of the ISFET in SPICE. *Sensors and Actuators, B: Chemical*, *62*(3), 182–189. https://doi.org/10.1016/S0925-4005(99)00377-9

Mauledoux, M., Aviles, O., Mejia-Ruda, E., & Caldas, O. I. (2016). Analysis of autoregressive predictive models and artificial neural networks for irradiance estimation. *Indian Journal of Science and Technology*, *9*(38). https://doi.org/10.17485/ijst/2016/v9i38/86214

Men, H., Ge, Z., Guo, Y., An, L., & Peng, Y. (2009). Biomimetic electronic tongue for classification of mineral water. *2009 International Conference on Measuring Technology and Mechatronics Automation, ICMTMA 2009*, *2*, 621–624. https://doi.org/10.1109/ICMTMA.2009.634

Mirin, S. N. S., & Wahab, N. A. (2014). Fault detection and monitoring using multiscale principal component analysis at a sewage treatment plant. *Jurnal Teknologi*, *3*(3), 87–92. https://doi.org/10.11113/jt.v70.3469

Milgrew, M. J., & Gumming, D. R. S. (2008). A proton camera array technology for direct extracellular ion imaging. *IEEE International Symposium on Industrial Electronics*, 2051–2055. https://doi.org/10.1109/ISIE.2008.4677310

Mokhtarifar, N., Goldschmidtboeing, F., & Woias, P. (2018). Low-cost EGFET-based pH-sensor Using Encapsulated ITO / PET-electrodes. *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 1–5.

Moser, N., Lande, T. S., & Georgiou, P. (2015). A novel pH-to-time ISFET pixel architecture with offset compensation. *Proceedings - IEEE International Symposium on Circuits and Systems*, *2015–July*, 481–484. https://doi.org/10.1109/ISCAS.2015.7168675

Moser, N., Lande, T. S., Toumazou, C., & Georgiou, P. (2016). ISFETs in CMOS and Emergent Trends in Instrumentation: A Review. *IEEE Sensors Journal*, *16*(17), 6496–6514. https://doi.org/10.1109/JSEN.2016.2585920

Nagtode, S. A., & Choudhari, N. K. (2013). A Review Paper on Electronic Sensor Based System to identify undesired ingredients present in Liquid. *International Journal of Application or Innovation in Engineering & Management (IJAIEM)*, *2*(2), 14–18.

Nakazato, K. (2009). Pen access an integrated isfet sensor array. *Sensors*, *9*(11), 8831–8851. https://doi.org/10.3390/s91108831

Narang, S. B., Singh, M., & Pubby, K. (2015). *Comparison of Feed Forward Neural Network Training Methods for Visual Character Recognition*. *2*(4), 366–369.

Nilsson. (2005). *American Associate for Artificial Intelligent*, AI Magazine 2005

Pan, T. M., Wang, C. W., Mondal, S., & Pang, S. T. (2018). Super-Nernstian sensitivity in microfabricated electrochemical pH sensor based on CeTixOy film for biofluid monitoring. *Electrochimica Acta*, *261*, 482–490. https://doi.org/10.1016/j.electacta.2017.12.163

Parizi, K. B., Xu, X., Pal, A., Hu, X., & Philip Wong, H. S. (2017). ISFET pH Sensitivity: Counter-Ions Play a Key Role. *Scientific Reports*, *7*(3), 1–10. https://doi.org/10.1038/srep41305

Popa, C., & Cernăzanu-glăvan. (2010). Pattern Neural Networks : A Case Study Training Pattern Neural Networks in Matlab. *2Nd Workshop on Spftware Services; Cloud Computing and Application Based on Software Services*.

Purushothaman, S., Toumazou, C., & Ou, C. P. (2006). Protons and single nucleotide polymorphism detection: A simple use for the Ion Sensitive Field Effect Transistor. *Sensors and Actuators, B: Chemical*, *114*(2), 964–968. https://doi.org/10.1016/j.snb.2005.06.069

Pyle, D. (1999). *Data Preparation for Data Mining*. Morgan Kaufmann

Rani, R. A., Syono, M. I., & Ramli, A. S. (2008). Multi-finger gate ISFET (Mf-ISFET) for pH sensor application. *IEEE International Conference on Semiconductor Electronics, Proceedings, ICSE*, 350–353. https://doi.org/10.1109/SMELEC.2008.4770339

Rani, R. A., & Sidek, O. (2004). ISFET pH Sensor characterization : towards Biosensor Microchip Application, 660–663.

Ruiz, L., Cuéllar, M., Calvo-Flores, M., & Jiménez, M. (2016). An Application of Non-Linear Autoregressive Neural Networks to Predict Energy Consumption in Public Buildings. *Energies*, *9*(9), 684. https://doi.org/10.3390/en9090684

Saini, D., Rupani, A., Sujediya, G., & Sharma, T. (2018). An ISFET automated output calibration system implementation on reconfigurable FPGA device with MATLAB artificial intelligence interfacing. *Proceedings of the 2017 3rd International Conference on Applied and Theoretical Computing and Communication Technology, ICATccT 2017*, (December 2017), 354–358. https://doi.org/10.1109/ICATCCT.2017.8389160

Sattler, K., & Box, P. O. (2001). *based on a Multidatabase Language*. 219–228.

Sharma, P., & Ugale, S. (2016). Electronic tongue based liquid identification using LVQ algorithm. *IEEE International Conference on Computer Communication and Control, IC4 2015*. https://doi.org/10.1109/IC4.2015.7375524

Shawkat, M. S. A., & McFarlane, N. (2017). A single-chip ISFET based pH sensor. *Proceedings of IEEE Sensors*, (1), 1–3. https://doi.org/10.1109/ICSENS.2016.7808833

Shepherd, L., & Toumazou, C. (2005). Weak Inversion ISFETs for ultra-low power biochemical sensing and real-time analysis. *Sensors and Actuators, B: Chemical*, *107*(1 SPEC. ISS.), 468–473. https://doi.org/10.1016/j.snb.2004.11.006

Shi, L., Cai, L., Li, E., Liang, Z., & Hou, Z. (2008). Nonlinear Calibration of pH Sensor Based on the Back-propagation Neural Network. *2008 IEEE International Conference on Networking, Sensing and Control*, 1300–1304. https://doi.org/10.1109/ICNSC.2008.4525418

Sohbati, M., Georgiou, P., & Toumazou, C. (2013). A piecewise linear approximating ISFET readout. *2013 IEEE Biomedical Circuits and Systems Conference, BioCAS 2013*, (2), 37–40. https://doi.org/10.1109/BioCAS.2013.6679634

Sohbati, M., & Toumazou, C. (2014). A temperature insensitive continuous time ΔpH to digital converter. *Proceedings - IEEE International Symposium on Circuits and Systems*, 37–40. https://doi.org/10.1109/ISCAS.2014.6865059

Sohbati, M., & Toumazou, C. (2015). Dimension and shape effects on the ISFET performance. *IEEE Sensors Journal*, *15*(3), 1670–1679. https://doi.org/10.1109/JSEN.2014.2365291

Sola, J., & Sevilla, J. (1997). Importance of input data normalization for the application of neural networks to complex industrial problems. *IEEE Transactions on Nuclear Science*, *44*(3 PART 3), 1464–1468. https://doi.org/10.1109/23.589532

Sundaram, S., & Sharma, N. N. (2010). Modeling interface diffusion as a mechanism for threshold voltage drift in pH sensors. *Proceedings of IEEE Sensors*, 2547–2550. https://doi.org/10.1109/ICSENS.2010.5690121

Taib, M. N., Bukhari, F., Suah, M., & Ahmad, M. (2005). An Intelligent Optical Fibre pH Sensor Based on Sol-Gel Advanced Material and Artificial Neural Network, *2*(2), 1–15.

Tzanis, G., Katakis, I., Partalas, I., & Vlahavas, I. (2006). Modern Applications of Machine Learning. *The 1st Annual SEERC Doctoral Student Conference*, 1–10.

Toumazou, C., Thay, T. S. L. K., & Georgiou, P. (2014). A new era of semiconductor genetics using ion-sensitive field-effect transistors: The gene-sensitive integrated cell. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *372*(2012). https://doi.org/10.1098/rsta.2013.0112

Uzzal, M. M., Zarkesh-Ha, P., Edwards, J. S., Coelho, E., & Rawat, P. (2014). A highly sensitive ISFET using pH-to-current conversion for real-time DNA sequencing. *International System on Chip Conference*, 410–414. https://doi.org/10.1109/SOCC.2014.6948964

Valenti, R., Sebe, N., Gevers, T., & Cohen, I. (2008). Machine learning techniques for face analysis. *Lecture Notes in Applied and Computational Mechanics*, 159–187. https://doi.org/10.1007/978-3-540-75171-7-7

Vojtko, J. (2004). Neural Network , Component of Measuring Set for Error Reduction, *4*, 1–10.

Woias, P., Meixner, L., & Fröstl, P. (1998). Slow pH response effects of silicon nitride ISFET sensors. *Sensors and Actuators, B: Chemical*, *48*(1–3), 501–504. https://doi.org/10.1016/S0925-4005(98)00032-X

Wu, D., Liu, X., Yu, H., Huang, X., Yan, M., & Jiang, Y. (2015). A Dual-Mode Large-Arrayed CMOS ISFET Sensor for Accurate and High-Throughput pH Sensing in Biomedical Diagnosis. *IEEE Transactions on Biomedical Engineering*, *62*(9), 2224–2233. https://doi.org/10.1109/tbme.2015.2419233

Xie, H., Tang, H. A. O., & Liao, Y. (2009). Time Series Prediction Based on Narx Neural Networks : an Advanced Approach. *Proceedings of the Eighth*

International Conference on Machine Learning and Cybernetics, (July), 12–15.

Xie, J., Myers, C. M., & Zhu, J. (2019). *Interactive Visualizer to Facilitate Game Designers in Understanding Machine Learning*. (March), 1–6. https://doi.org/10.1145/3290607.3312851

Xu, X., & Hines, J. W. (1997). Sensor Calibration and Fault Detection Using Neural Network Techniques. *Proceedings of Maintenance and Reliability Conference*.

Zolkapli, M., Ya, N., Aziz, A. A., Zoolfakar, A. S., Manut, A., Fazlida, W., … Adenan, H. B. (2018). Neural Network Algorithm Development for Ion Sensitive Field Effect Transistor (ISFET) Sensor, *7*, 1–5.